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OPTIMIZING THE USE OF CROP RESIDUES FOR SOIL QUALITY AND PRODUCTIVITY, AND ON-FARM AND OFF-FARM USES IN THE GRAY SOIL ZONE

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Optimizing the Use of Crop Residues for Soil Quality and Productivity, and On-Farm and Off-Farm Uses in the Gray Soil Zone

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Optimizing the use of crop residues for soil quality and productivity, and on-farm and off-farm uses in the Gray soil zone

Abstract

Management practices, such as elimination of tillage and returning of crop residue, improve soil quality, sustain high crop production and minimize environmental damage. The objective of this study was to determine the effects of tillage and crop residue management on seed and straw yield, N uptake and C removal in crop, soil organic C and N, inorganic N and aggregation, and nitrous oxide (N_2O) emissions in the second 4-yr rotation cycle (2002-2005) on a Gray Luvisol (Boralf) soil near Star City, Saskatchewan, Canada. The 8-yr (1998-2005) field experiment was conducted with two tillage systems (no tillage -NT and conventional tillage - CT), two levels of straw (straw retained -S) and straw removed -NS), and four rates of fertilizer N (0, 40, 80 and 120 kg N ha^{-1}, except no N to pea phase of the rotation). The plots were seeded to barley (*Hordeum vulgare* L.) in 2002, pea (*Pisum sativum* L.) in 2003, wheat (*Triticum aestivum* L.) in 2004 and canola (*Brassica napus* L.) in 2005. No-till produced greater seed, straw and chaff yield of barley than CT in 2002, but seed and straw yield were generally greater under CT than NT for wheat in 2004 and for canola in 2005. Straw retention increased seed, straw and chaff yield, and root mass compared to straw removal for barley in 2002, wheat in 2004, and seed and straw yield for pea in 2003. Seed, straw and chaff yield, and root mass increased with increasing N rate for barley in 2002, wheat in 2004 and canola in 2005. No-till resulted in greater N uptake in seed, and C removed in seed, straw, chaff and root than CT for barley in 2002, but N uptake and C removed were usually greater under CT than NT for wheat in 2004 and for canola in 2005. Straw retention had greater N uptake and C removed in seed, straw, chaff and root in most cases compared to straw removal for barley in 2002, pea in 2003 and wheat in 2004. The amount of N uptake and C removed in barley, wheat and canola increased substantially with increasing N rate. Soil moisture content in spring was higher under NT than CT and with S than NS in the 0-15 cm depth, with the highest moisture content with NT + S treatment in many cases. After eight crop seasons, tillage and straw management had no significant effect on total organic C (TOC) and N (TN) in the 0-15 cm soil, but light fraction organic matter (LFOM), C (LFC), and N (LFN) were generally greater with S than NS, and also greater or tended to be greater under NT than CT. There was no effect of tillage, straw and N

fertilization on NH_4-N in soil, but S tended to have higher NO_3-N concentration in 0-15 cm soil than NS. The concentration of NO_3-N (though small) tended to increase with N rate in the 0-15, 15-30 and 30-60 cm soil layers. The S treatment had a lower proportion of fine (<0.83 mm diameter), and greater proportion of large (>38.0 mm) dry aggregates and larger mean weight diameter (MWD) compared to NS treatment. This suggests a lower potential for soil erosion when crop residues are retained. There was no benefit of elimination of tillage on the improvement of soil aggregation. Amount of N lost as N_2O was higher from N-fertilized than from zero-N plots, and was greater in CT than NT in some cases. Retaining crop residues along with no-tillage improved some soil properties and may also be better for the environment and the sustainability of high crop production.

Executive Summary

Sustainability of agriculture production and soil quality has been linked to organic matter, which in turn is mainly a function of crop residue addition to soil. In the Parkland region, however, large amounts of straw are produced by cereal crops and too much residue left on soil surface can be a management problem. Successful integration of crop residue management strategies into sustainable cropping systems, however, requires an understanding of how crop residues influence cycling of nutrients and soil properties. Management practices, such as elimination of tillage and returning of crop residue, improve soil quality, sustain high crop production and minimize environmental damage. The objective of this study was to determine the effects of tillage and crop residue management on seed and straw yield, N uptake and C removal in crop, soil organic C and N, inorganic N and aggregation, and nitrous oxide (N_2O) emissions in the second 4-yr rotation cycle (2002-2005) on a Gray Luvisol (Boralf) soil near Star City, Saskatchewan, Canada. The 8-yr (1998-2005) field experiment was conducted with two tillage systems (no tillage -NT and conventional tillage - CT), two levels of straw (straw retained -S) and straw removed -NS), and four rates of fertilizer N (0, 40, 80 and 120 kg N ha^{-1}, except no N to pea phase of the rotation). The plots were seeded to barley (*Hordeum vulgare* L.) in 2002, pea (*Pisum sativum* L.) in 2003, wheat (*Triticum aestivum* L.) in 2004 and canola (*Brassica napus* L.) in 2005. No-till produced greater seed, straw and chaff yield of barley than CT in 2002, but seed and straw yield were generally greater under CT than NT for wheat in 2004 and for

canola in 2005. Straw retention increased seed, straw and chaff yield, and root mass compared to straw removal for barley in 2002, wheat in 2004, and seed and straw yield for pea in 2003. Seed, straw and chaff yield, and root mass increased with increasing N rate for barley in 2002, wheat in 2004 and canola in 2005. No-till resulted in greater N uptake in seed, and C removed in seed, straw, chaff and root than CT for barley in 2002, but N uptake and C removed were usually greater under CT than NT for wheat in 2004 and for canola in 2005. Straw retention had greater N uptake and C removed in seed, straw, chaff and root in most cases compared to straw removal for barley in 2002, pea in 2003 and wheat in 2004. The amount of N uptake and C removed in barley, wheat and canola increased substantially with increasing N rate. Soil moisture content in spring was higher under NT than CT and with S than NS in the 0-15 cm depth, with the highest moisture content with NT + S treatment in many cases. After eight crop seasons, tillage and straw management had no significant effect on total organic C (TOC) and N (TN) in the 0-15 cm soil, but light fraction organic matter (LFOM), C (LFC), and N (LFN) were generally greater with S than NS, and also greater or tended to be greater under NT than CT. There was no effect of tillage, straw and N fertilization on NH_4-N in soil, but S tended to have higher NO_3-N concentration in 0-15 cm soil than NS. The concentration of NO_3-N (though small) tended to increase with N rate in the 0-15, 15-30 and 30-60 cm soil layers. The S treatment had a lower proportion of fine (<0.83 mm diameter), and greater proportion of large (>38.0 mm) dry aggregates and larger mean weight diameter (MWD) compared to NS treatment. This suggests a lower potential for soil erosion when crop residues were retained. There was no benefit of elimination of tillage on the improvement of soil aggregation. Amount of N lost as N_2O was higher from N-fertilized than from zero-N plots, and was greater in CT than NT in some cases. Retaining crop residues along with no-tillage improved some soil properties and may also be better for the environment and the sustainability of high crop production.

Technical Report

1. Introduction

High and sustainable crop production is linked to improved soil physical, chemical and biological properties, which in turn are a primary function of soil organic matter. No-tillage with standing stubble conserves soil, organic matter and water, and generally increases crop

production (Zentner and Lindwall, 1978; Philips et al., 1980). Crop residues are a source of organic C for soil microorganisms and also contribute to plant nutrients. The fertilizer N equivalent credit from crop residues was suggested as 8-10 kg N ha^{-1} for oilseed rape in Denmark (Thomsen and Christensen, 1996), while Beckie (1997) estimated a 28 kg N ha^{-1} credit to crops that follow peas. Cereal residues, however, contribute little immediate plant-available N to the soil because of their wide C:N ratios.

Straw is a valuable resource for on-farm animal feed and off-farm fuel and paper products. Stumborg et al. (1996) estimated the value of cereal straw to be about \$16 ha^{-1}. In the Parkland region of western Canada, large quantities of cereal straw are produced, which if left on soil surface can sometimes pose a management problem. In these areas, there may be opportunities for removing straw for alternative uses while maintaining optimum soil organic matter level. Before recommending straw removal, however, the impact of this practice on crop yield and soil properties must be assessed. Management options such as no-tillage (NT) (Saffigna et al., 1989; Halvorson et al., 2002), choice of crops in a rotation and rotation length (Havlin et al., 1990; Janzen et al., 1992; Soon and Arshad, 1996), and adequate fertilization (Nyborg et al., 1995b) can be used to enhance the level of organic matter in soil, which might offset the potentially negative impact of residue removal. These practices have shown promise for the Black soil (Boroll) zone of Canadian prairies (Nuttall et al., 1986; Campbell et al., 1991), but information is lacking for the Gray soil (Boralf) zone, especially when different crops are grown in a rotation.

Tillage, residue and N fertilization also affect nitrate-N concentration, water content, aeration and available C (Rice and Smith, 1982; McKenny et al., 1993) which, in turn, can impact N loss through denitrification and N_2O emissions (Rice and Smith, 1982; Fan et al., 1997; MacKenzie et al., 1997; Baggs et al., 2003). Generally higher N_2O emissions from NT compared to conventional-till (CT) systems have been reported (Burford et al., 1981; Linn and Doran, 1984; MacKenzie et al., 1997). Lemke et al. (1999) however, measured lower emissions from NT compared to CT for Black and Gray soils in north-central Alberta. In a recent review of Canadian data, Helgason et al. (2005) found that N_2O emissions were more often reported to be higher for NT compared to CT in more humid regions (eastern Canada), but reverse was true in the drier prairie region. Crop residues, particularly N-rich legume residues, are generally thought to

stimulate N_2O emissions (Baggs et al., 2000; Huang et al., 2004). However, Hao et al. (2001) found that removing residue actually decreased N_2O emissions from an irrigated soil in southern Alberta, particularly on plots tilled in autumn after harvest. Their study suggested a complex interaction between timing of tillage and N application, and residue management. While increasing fertilizer N rates will most likely increase N_2O emissions (Bouwman, 1996), the relative impact of different tillage and residue management combinations and the potential interaction with N application remains uncertain.

Successful integration of crop residue management strategies into cropping systems requires an understanding of how crop residues influence cycling of nutrients from soil and fertilizers, as well as their effects on soil chemical, physical and biological properties, and crop production. Information is needed as to whether crop residues can be removed from cropping systems for alternative uses without detrimental impact on soil properties, productivity and the environment. Results of the first 4-yr rotation cycle on these parameters were reported previously (Malhi et al., 2006). The changes in soil properties due to tillage and crop residue management practices and their impact on crop yield and nutrient uptake is a slow process. So, the objective of this study was to determine the influence of tillage, crop residue management and N rate on crop yield, N uptake and C removal, soil organic C and N, inorganic N and aggregation, and nitrous oxide (N_2O) emissions in the second 4-yr rotation cycle on a Gray Luvisol (Boralf) in northeastern Saskatchewan, Canada.

2. Materials and Methods

An 8-yr (1998-2005) field experiment with two 4-yr rotations was conducted near Star City in northeastern Saskatchewan, Canada (52° 52′ N, 104° 20′ W). Soil at the site was a Gray Luvisol (Boralf) with sandy clay loam texture and pH of 7.1. Mean annual air temperature, precipitation and evapotranspiration in the area is 0.3°C, 410 mm and 506 mm, respectively. Long-term average precipitation in the growing season (May, June, July and August) is about 244 mm. The growing season precipitation at the nearest Environment Canada Meteorological Station (Melfort Research Farm) was 250 mm in 2002 (near-average, but very dry in May, June and July with only 119 mm precipitation compared to long-term average of 187 mm), 169 mm in

2003 (below average), and 290 mm in 2004 (above-average) and 372 mm 2005 (above-average). The experiment was a 2 x 2 x 4 factorial with four replications in a randomized complete block design. The treatments included two tillage systems: no tillage (NT), and conventional tillage (CT); two levels of straw: straw retained (S), and straw removed (NS); and four levels of fertilizer N: 0, 40, 80, and 120 kg N ha^{-1}, except that no N was applied to pea (*Pisum sativum* L.) phase of the rotation. Individual plots were 3.6 m x 15 m.

The site was under barley (*Hordeum vulgare* L.) in 1997. Prior to this the site was under CT, with annual cereals and oilseeds in rotation. During each year of the experiment, straw was removed from the NS plots and returned to S plots after crop harvest in late August or early September. The CT plots were rototilled to 10 cm depth once in autumn and once in spring each year. The NT plots were sprayed with glyphosate (Roundup^{TM}) for weed control in spring prior to seeding. Blanket annual applications of fertilizers to supply 30 kg phosphorus, 42 kg potassium and 17 kg sulphur ha^{-1} were broadcast in all plots prior to tillage and sowing in spring. Nitrogen fertilizer was side-banded 2.5 cm away and 2.5 cm below seed rows at sowing. The plots were seeded to barley (cv. AC Lacombe) in 2002, peas (cv. Alfetta) in 2003, wheat (*Triticum aestivum* L. cv. AC Barrie) in 2004 and canola (*Brassica napus* L. cv. 45A71) in 2005. Seed rate was 108, 202, 134, and 9 kg ha^{-1} and seeding depth was 3.8, 4.5, 4.4, and 1.9 cm for barley, peas, wheat, and canola, respectively. Each year the crop was seeded in May with a ConservaPack drill equipped with knives in 22.5 cm rows. Appropriate herbicides were used in all plots for in-crop weed control.

At crop maturity, a 1-m length of two rows per plot was harvested for dry matter determination. The samples were thrashed to determine seed:straw:chaff ratios. Seed yield was determined by harvesting 5 rows in the centre of each plot using a combine. Seed yields in combination with seed:straw:chaff ratios from dry matter samples were used to calculate straw and chaff yields. Root mass was determined by digging out 0-15 cm soil from 45 cm x 45 cm area. Soil adhering to the roots was gently removed using a screen with 4-mm holes. Root samples were washed and dried at 60°C. Representative seed, straw, chaff and root samples were analyzed using CNS combustion analyzer for total N (TN) (AOAC, 1995) and total organic C (TOC) (Nelson and Sommers, 1996).

Soil samples were collected in the autumn of 2005 from 0-5, 5-10 and 10-15 cm depths at

8 locations per plot using a 2.4 cm diameter coring tube. Bulk density of soil was determined by the core method (Culley, 1993). The samples were air dried at room temperature after removing coarse roots and easily detectable crop residues, and ground to pass through a 2-mm sieve. Sub-samples were pulverized in a vibrating-ball mill (Retsch, Type MM2, Brinkman Instruments Co., Toronto, Ontario). The method of Technicon Industrial Systems (1977) was used to determine TN in the soil. Light fraction organic matter (LFOM) was separated using a NaI solution of 1.7 Mg m^{-3} specific gravity, following the method described by Janzen et al. (1992) and modified by Izaurralde et al. (1998). The C and N in LFOM (LFC, LFN) were measured by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy). The NO_3-N and NH_4-N were extracted using 1:5 soil:2M KCl solution and their concentrations in extracts were measured with a Technicon Autoanalyzer II (Technicon Industrial Systems, 1973a, b).

In the autumn of 2005, soil samples for dry aggregates were collected from 0-5 cm depth at two inter-row locations in each plot using a rectangular trough (15 cm x 17.5 cm) with minimal disturbance. The soil was air dried to about 5 g water 100 g^{-1} soil. The samples were shaken, using an automatic rotary sieve shaker, at 12 cycles per minute, through a nest of sieves with equivalent diameter of 38, 12.7, 6.4, 2.0, 0.83, and 0.42 mm, and a pan underneath. Aggregate fraction retained on each sieve and the pan was expressed as a percentage of total dry soil mass. The results were expressed as percent aggregate size distribution as well as mean weight diameter (Van Bavel, 1950). Any coarse roots detected in the soil after sieving were removed by hand.

Nitrous oxide (N_2O) emissions and soil water content were measured between late spring and early summer from the zero-N and 120 kg N ha^{-1} fertilizer treatments on both NT and CT with and without residue. Sampling was conducted from May 29 to September 19 (114 days) in 2002, from April 15 to July 5 (75 days) in 2003, from April 14 to August 31 (140 days) in 2004, and from April 6 to October 12 (190 days) in 2005. Treatments were sampled on the same day once or twice weekly using soil chambers as described by Corre et al. (1996). Nitrous oxide flux was estimated from the concentration change in the chamber headspace over a 60 min period. Samples were drawn from the headspace by fully filling disposable 20 ml polypropylene syringes. Gas samples were then injected into pre-evacuated 13 ml exetainer glass tubes for

transport to the laboratory. The concentration of N_2O in the samples was determined using a gas chromatograph equipped with an electron capture detector. The calculated minimum detectable difference for the system was <10 ppbv. Cumulative estimates were calculated by interpolating between data points and integrating over time assuming a constant flux (Lemke et al., 1999). Soil samples were also taken every year in spring from the 0-15, 15-30, 30-45 and 45-60 cm depths for moisture content in soil prior to seeding. Soil moisture was determined by a gravimetric method on a mass basis.

Data were analyzed for analysis of variance (ANOVA) using a factorial structure of the treatments (SAS Institute Inc., 1993). Least significant difference ($LSD_{0.05}$) was used to determine significant differences between treatment means.

3. Results and Discussion

3.1. Crop yield

3.1.1. Tillage and straw effects

Tillage had no effect on seed, straw and chaff yield, and root mass for pea in 2003, but had significant effect on seed, straw and chaff yield for barley in 2002, seed yield and root mass for wheat in 2004, and seed and straw yield for canola in 2005 (**Table 1**). No-tillage produced greater seed, straw and chaff yield for barley in 2002 and root mass for wheat in 2004 than CT, but seed and straw yield were greater or tended to be greater under CT than NT for wheat in 2004 and for canola in 2005. Straw management had significant effect on almost all the measured crop parameters for barley in 2002, pea in 2003 and wheat in 2004, but had no effect on canola in 2005. Straw retention increased seed, straw, chaff and root yield compared to straw removal for barley in 2002, pea in 2003 and wheat in 2004.

Seed, straw and chaff yield of barley in 2002 were significantly greater with NT compared with CT by 51, 23, and 13%, respectively. Seed, straw and chaff yield, and root mass were greater with S compared with NS by 62%, 43%, 12% and 11%, respectively. A tillage x straw management interaction was significant only for seed yield and root mass for barley in 2002 and

for seed yield for wheat in 2004 (**Table 2**). The seed yield and root mass in 2002 were greatest with NT + S, but in 2004 seed yield was greatest with CT + S. In 2002, straw retention increased yield of seed and straw yield, respectively by 81% and 51% under NT, and by 38% and 35% under CT. The corresponding increase for root mass was 22% under NT, but there was no increase in root mass under CT. The beneficial effect of straw retention on barley yield thus appeared to be generally greater with NT than with CT.

The beneficial effect of NT and straw return on crop yield is accomplished mainly through conservation of soil moisture in a dry year or in a dry region, and improvement in soil properties (which is a slow process). The greater yield of barley under NT compared to CT (particularly where straw was returned) in 2002, a year with below-average precipitation in the early and peak growing season (May, June and July), was most likely associated with better conservation of water under NT, as evidenced by higher early spring soil moisture content in NT and S plots than CT and NS plots, respectively (**Table 7**). For example, soil moisture content was higher in NT than in CT by 1.5% in 0-15 cm and by 1.9% in 15-30 cm depth, and also higher in S than in NS by 1.9% in 0-15 cm and by 2.6% in 15-30 cm depth. In years with above-average precipitation in the growing season (2004 and 2005), the crop yield was in fact greater with CT than NT. In 2003 growing season with below-average precipitation, there was no positive influence of NT and S treatment on the yield of pea. This may be due to the nature of the crop (less moisture demanding crop or efficient user of soil moisture). The greater seed, straw and chaff yield, and root mass in 2002, 2003 and 2004 on S compared to NS suggests an improvement in soil productivity on the S treatments.

3.1.2. Nitrogen effects

Seed, straw, chaff and root yield increased with increasing N rate for barley in 2002, wheat in 2004 and canola in 2005 (**Table 1**). Seed yield and root mass of barley in 2002 increased with applied N to 80 kg ha^{-1}, while straw and chaff yield continued to increase with applied N up to 120 kg N ha^{-1}. The increases with the first and second increment of 40 kg N ha^{-1}, respectively were 76% and 9% for seed yield, 81% and 13% for straw yield, 43% and 4% for chaff yield, and 39% and 10% for root mass. This indicated that the major response of yield parameters to applied

N was with the initial 40 kg N ha^{-1} rate. In general, the 2003 pea crop showed little response of straw and chaff yield to residual N from that applied to crops in previous years.

Yield components of wheat in 2004 responded to applied N in a fashion similar to barley in 2002 (**Table 1**). Seed and chaff yield of wheat increased with applied N to 80 kg ha^{-1}, while straw yield continued to increase with applied N up to 120 kg N ha^{-1}. Chaff yield increased only with the first 40 kg N ha^{-1} increment. Seed and straw yield increased respectively by 35% and 35% with the first 40 kg N ha^{-1} and by 7% and 14% with the second N increment. Seed, straw and chaff yield and root mass of canola responded strongly to applied N, with significant increase of 80%, 67%, 46%, and 50%, respectively, with the first 40 kg N ha^{-1} compared to no N (Table 1). Seed yield and root mass continued to increase with applied N up to 120 kg N ha^{-1} and straw and chaff yield responded up to 80 kg N ha^{-1}.

Tillage x N rate interaction was significant for barley seed yield in 2002 and wheat straw yield in 2004 (**Table 3**). Straw management x N rate interaction was significant for barley seed yield in 2002, and canola seed and straw yield in 2005. These interactions indicated that seed and/or straw yield response to increasing N was usually greater under NT than CT, and also greater with S than with NS. This was most likely due to greater soil water storage and improvement in soil quality when tillage was eliminated and/or crop residues were returned to soil, which increased crop growth and yield at higher N rates, to a maximum at 120 kg N ha^{-1}. In this experiment, N rate did not affect soil moisture content in the 0-15 cm depth, but it was higher under NT than CT, and also higher with S than NS (**Table 7**). This was most likely due to increased production of crop residues and standing stubble in the NT + S treatment (or CT + S in some cases), which would trap more snow over the winter, and reduce run-off from snow melt in early spring and evapotranspiration during the growing season, leaving more water in soil for plant use. In a relatively dry area (or in a dry year) when soil moisture limits plant growth, moisture conservation using NT has been shown to produce higher crop yield in the Canadian Prairies (Lindwall and Anderson, 1981; Malhi et al., 2006).

In the initial years after adopting NT and where N fertilizer was broadcast, retaining cereal straw on the soil has been found to reduce crop yield compared to removal, likely due to increased immobilization of N caused by the addition of straw with a wide C:N ratio (Tomar and Soper, 1981; Malhi et al., 1989; Nyborg et al., 1995a). However, when an appropriate rate of N

fertilizer was properly placed in the soil, or when the soil had adequate amounts of mineral N, yield of barley in the P cland region of Alberta was similar under NT and CT (Nyborg and Malhi, 1989; Malhi and Nyborg, 1990, 1992; Nyborg et al., 1995a). In another study in the same region, Wani et al. (1994) found higher barley seed yield on a continuous cereal rotation with straw retained compared to a 5-year rotation with residues removed. In the present study, crop yield was greater with S than NS in most cases, and also greater under NT than CT in some cases at all N fertilizer rates, most likely due to greater water conservation in soil under NT and/or S which increased yield response to applied N.

3.2. Amount of N uptake and C removal in crop

3.2.1. Tillage and straw effects

In the 2002 barley crop, tillage had a significant effect on the amount of N uptake in seed, and on C removed in seed, straw, chaff and root. Straw management had a significant effect on N uptake in seed and straw, and on C removal in all crop yield parameters (**Table 4**). The amount of N uptake and C removed was greater under NT than CT, and also greater with S than NS. In earlier research in the Parkland region of Alberta, Malhi and Nyborg (1990) also observed similar or greater N uptake of barley under NT than CT with applied N on a Gray Luvisol soil.

In 2003, the main effect of straw management was significant on the amount of N uptake and C removed in seed, straw and chaff yield of pea. In the 2004 wheat crop, the amount of N uptake in seed and straw was greater in S compared to NS. The amount of C removed in seed, straw and chaff was significantly greater with S compared to NS treatment. The amount of N uptake and C removed in root was greater under NT than CT, but the opposite was true for N uptake and C removed in seed. In 2005, the amount of N uptake and C removed was greater under CT compared to NT in canola seed and straw. There was no effect of straw management on the amount of N uptake and C removed for any yield parameter.

There was a significant tillage x straw interaction for N uptake and C removed in seed and root of barley in 2002, N uptake in pea straw in 2003, N uptake and C removed in wheat seed in 2004, and C removed in canola straw in 2005 (**Table 5**). Tillage x straw interaction

resulted in highest values of N uptake and/or C removed in plant components in NT + S treatment in 2002 and 2003, but in 2004 and 2005 the N uptake and/or C removed was highest in the CT + S treatment.

3.2.2. Nitrogen effects

In the 2002 barley crop, the amount of N uptake and C removed in seed, straw, chaff and roots were significantly increased with N fertilization (**Table 4**). The N uptake and C removed continued to increase with increasing N rate to 120 kg N ha^{-1} in almost all cases. The increase in straw yield, chaff yield and root mass, and the amount of C removed in straw, chaff and root with N fertilization indicated that some of the straw removal effect on soil organic matter could be mitigated by N fertilization. For example, when N rate was increased from 0 to 80 kg N ha^{-1}, straw yield, chaff yield and root mass were increased by 740, 157 and 310 kg ha^{-1}, respectively. Thus, an extra 341, 68 and 114 kg C ha^{-1} were added to soil by straw, chaff and roots, respectively.

The 2003 pea crop showed little response to previous N additions in terms of N uptake and C removed in seed, straw, chaff or root. In both wheat in 2004 and canola in 2005, the amount of N uptake and C removed in seed, straw, chaff, and root increased substantially with increasing N rate. For example, the amount of N uptake and C removed in wheat seed with 80 kg N ha^{-1} was, respectively, 88% and 66% greater than zero-N control. Corresponding increases in canola seed were 237 and 174%. The amount of N uptake and C removed were greater with 80 kg N ha^{-1} compared to zero-N, respectively by 80% and 41% in wheat roots, and by 142% and 66% in canola roots.

Tillage x N rate interaction was significant for C removed in barley seed in 2002, N uptake in pea root and C removed in pea chaff in 2003, and C removed in wheat straw in 2004 (**Table 6**). Straw x N rate interaction was significant for N uptake in seed, straw and root and C removed in seed, chaff and root in 2002, N uptake and C removed in pea seed in 2003, and C removed in canola seed and straw in 2005 (**Table 6**). In 2005, the straw x N rate interaction was significant only for C removed in seed and straw, with higher values in S than NS treatments. This resulted in highest response of N uptake and/or C removed in plant components to applied

N under NT or S compared to CT or NS treatments in most cases.

Greater amount of N uptake and C removal by crops was ascribed to improvement in above-ground plant growth and root growth with N application, resulting in increased N uptake and sequestration of C from atmosphere through photosynthesis. Halvorson et al. (2001) also reported increased grain N uptake with N rate in most of the 12 cropping seasons of an annual cropping system in the northern Great Plains. Earlier studies in the Canadian Parkland region showed N uptake to be lower under NT compared to CT at low N rates, but similar at near optimum N rates (Malhi and Nyborg, 1990; Nyborg et al., 1995a). For annual cropping systems in the northern Great Plains, greater grain yield with NT compared to CT was considered to contribute to greater removal of N in grain (Halvorson et al., 1999a), and the N uptake with NT was lower at lower N rates and higher at higher N rates (Halvorson et al., 2001).

3.3. Soil properties

3.3.1. Soil moisture content

Omitting tillage and retaining straw often improves the capacity of soil to store water (Moody et al., 1963; Jones et al., 1969; Shanholtz and Lillard, 1969; Nyborg and Malhi, 1989; Malhi and O'Sullivan, 1990; Singh et al., 1998; Malhi et al., 2006). Similarly, soil moisture content in spring in the present study was higher with S than NS in the 0-15 cm depth in all years and in the 15-30 cm depth in 2002, and also higher under NT than CT in some cases (**Table 7**). There was no effect of N rate on spring soil moisture content. Tillage x straw interaction effect on soil moisture was significant for 45-60 cm depth in 2002, 30-45 cm in 2003, 0-15 and 45-60 cm in 2004 and 45-60 cm in 2005 (**Table 8**). This resulted in highest soil moisture in the NT + S treatment in many cases. Tillage x N rate interaction was significant only for 15-30, 30-45 and 45-60 cm depths in 2002, with highest soil moisture content under NT at 120 kg N ha^{-1} rate in 2 of 3 cases (**Table 9**). Straw x N rate interaction effect was significant in only 0-15 cm depth in 2005, where soil moisture content was highest in S treatment at 120 kg N ha^{-1} rate.

3.3.2. Soil organic C, organic N and mineral N

After eight crop seasons, tillage and straw management had no significant effect on total organic C (TOC) and N (TN) in the top 15 cm of soil, but light fraction organic matter (LFOM), C (LFC), and N (LFN) were generally greater with S than NS, and also greater or tended to be greater under NT than under CT (**Table 10**). Tillage x straw, tillage x N rate, straw x N rate and tillage x straw x N rate interactions were generally not significant at $P \leq 0.05$. Compared to NS, the S treatment increased LFOM by 12%, LFOC by 24%, and LFN by 10%. Increase in organic C and N fractions due to straw retention was closely associated with greater input of C and N to soil through straw, chaff and roots in the S compared to NS treatments. The lower mass of soil C and N with NS than S suggests that the practice of removing straw from fields for on-farm and industrial uses in the long run may result in soil degradation (Campbell et al., 1998).

Previous research has shown a substantial increase of total organic C in soil under NT compared to CT (Halvorson et al., 2002). But in the present study, there was no significant increase in TOC and TN with NT compared to CT, although LFOM, LFC, and LFN were greater or tended to be greater under NT than under CT. Nitrogen rate had no effect on TOC and TN, but significantly increased LFOM, LFC, and LFN (**Table 10**).

Build-up of organic matter in soil is a slow process and it takes many years to accumulate significant amounts. That is why in the present 8-year study many effects, especially of tillage and N rate, and particularly on TOC and TN, were not significant. Campbell et al. (1998) reported that 6 years of NT on a thin Black Chernozem in Saskatchewan, Canada, did not increase TOC or TN, but removal of straw in a fallow-wheat-wheat rotation tended to reduce TOC and TN. In long-term studies in Alberta, build-up of TOC and TN with straw retention compared to straw removal was seen in one soil with low inherent organic matter, and the effect of straw was greater than that of tillage (Nyborg et al., 1995b; Solberg et al., 1998). However, in a 19-yr study in Australia, effect of tillage on TOC and aggregation was much greater than stubble management (Chan et al., 2002).

Earlier research has shown accumulation of nitrate-N in the soil profile when excessive rate of N fertilizer was applied (Campbell et al., 1994; Guillard et al., 1995). The soil NO_3-N level in annual cropping system in northern Great Plains was observed to increase with N rate and greatest increase was at the highest rate (101 kg N ha^{-1}) (Halvorson et al., 1999b). Similarly,

at the end of first 4-yr rotation cycle in 2001 in this experiment, there was a considerable increase in NO_3-N concentration in soil with increasing rate of applied N (Malhi et al., 2006). However, at the end of second 4-yr rotation cycle of this experiment, the increase in NO_3-N concentration from applied N was small, but significant (**Table 11**). This was most likely due to increased uptake of applied N from improved soil moisture conditions in 2004 and 2005. The S treatment tended to have higher NO_3-N concentration in 0-15 cm soil than NS. There was no effect of tillage, straw management or N rate on the concentration of NH_4-N in the soil.

3.3.3. Soil aggregate size distribution

At the end of 8 years, the S treatment had a lower proportion of fine (<0.83 mm diameter) and a greater proportion of large (>38.0 mm) dry aggregates compared to NS treatment (**Table 12**). Addition of straw on average increased the proportion of large aggregates by 68% and decreased the proportion of small aggregates by 35%. Combining S with CT or NT decreased the proportion of small aggregates by 6-8% and increased the proportion of large aggregates by 9% compared to CT + NS or NT + NS treatments. If dry aggregates <0.83 mm are considered the wind-erodible fraction (Siddoway, 1963; Skidmore et. al., 1986), then the S treatments tended to have lower percentage of wind-erodible aggregates and higher percentage of large aggregates compared to NS treatments under both CT and NT. This indicates reduced potential for soil erosion when crop residues were retained.

The beneficial influence of S was also reflected in mean weight diameter (MWD) of aggregates, which was greater with S (22.8 mm) than with NS (18.3 mm) (**Table 12**). On average, the MWD was 25% greater with S than with NS. The MWD tended to be larger for S than NS under both tillage systems. As the quality of soil structure in the seed bed is strongly related to size distribution of air-dry aggregates (Braunack and Dexter, 1989), these results indicate a better seed-bed soil structural condition and lower potential for soil erosion by wind when crop residues are returned to the soil. Our aggregation data indicates a large impact of straw management on the improvement of soil aggregation under both tillage systems and no additional improvement in aggregation with elimination of tillage. In fact, aggregation slightly decreased with NT compared to CT and there is no explanation for that trend. Other research in the

Canadian prairies has demonstrated greater effects of tillage than straw management on aggregation of soil under barley cultivation (Singh et al., 1994; Singh and Malhi, 2005).

The proportion of small aggregates was slightly greater (by 3%), but significant, and the proportion of large aggregates was slightly lower (by 5%), but significant, in the surface soil of NT compared to CT (**Table 12**). That is, the NT systems tended to have higher percentage of wind-erodible aggregates and lower percentage of large aggregates than CT under both S and NS treatments. The MWD of aggregates was on average greater by 2.6 mm with CT as compared with NT. This is contrary to findings previously reported by Singh et al. (1994) and Singh and Malhi (2006). The proportion of large aggregates tended to increase and proportion of small aggregates significantly decreased with increasing N rate from 0 to 120 kg N ha^{-1} (**Table 12**). This could be due to the return of greater amounts of crop residue from increased crop yield and subsequent higher storage of light fraction organic matter in soil with increasing rate of applied N.

3.4. Nitrous oxide emissions

In a general way, the magnitude of cumulative N_2O loss reflected precipitation levels. During 2002 and 2003 when precipitation was at or below long-term average, the mean cumulative N_2O loss did not exceed 300 g N ha^{-1}. It should be noted however, that the rotation was in the pea phase during 2003 thus no fertilizer N was applied. Recent work has indicated that on the Canadian prairies, N_2O emissions from pulse crops during the growing season tend to be low (Zhong, 2006; Lemke et al., 2002). During 2004 and 2005 when precipitation was considerably higher than the long-term average, losses ranged as high as 1300 g N ha^{-1} (**Table 13**). The range of cumulative N_2O emission values are consistent with those reported during the first 4-year cycle of this study (Malhi et al. 2006) and for other studies conducted under similar environmental conditions (Lemke et al., 1999; Corre et al., 1996).

Cumulative N_2O loss was not influenced by tillage system in 2002, 2003 or 2005, but emissions from NT were significantly lower than CT treatments in 2004 (**Table 13**). Similar or lower emissions from NT compared to CT is contrary to results from many other regions (Baggs et al., 2003; MacKenzie et al., 1997), but is in agreement with previous work in the Canadian

Parkland region (Lemke et al., 1999) and with results reported for the first 4-year cycle of this study (Malhi et al., 2006). Fertilizer N application significantly and consistently increased N_2O emissions, as also has been observed in earlier research (Bouwman, 1996). No fertilizer N was applied during the pea phase of the rotation in 2003 and we assume that the increased emissions from the "fertilized" plots reflected a residual effect from applications in previous years. The increase in N_2O emissions associated with fertilizer N was much greater on CT compared to NT in 2004, resulting in a significant tillage x fertilizer interaction.

Straw management had no significant influence on cumulative N_2O emissions (**Table 13**). This is of particular interest as the N contained in crop residues is assumed to stimulate N_2O emissions (IPCC 1997). Other researchers have reported increase in N_2O emissions with crop residue applications (Baggs et al., 2000). It is not clear why the presence or absence of residues had no influence on N_2O emissions in this study. The influence of residue management on N_2O emissions is complicated by many factors including the timing of incorporation and fertilizer application (Hao et al., 2001) and environmental conditions. It is possible that the pattern of N and C availability relative to the concurrent soil environmental conditions (e.g. soil-water content, soil temperature) in this region is such that straw return after harvest has little impact on N_2O loss potential. As well, even on the "straw removed" treatments a portion of the straw (stubble), most of the chaff, and all of root mass remained in the field. It is possible that the additional straw left on the "straw retained" treatments simply had no incremental influence. Clearly more work is needed to clarify the relationship between residue management and N_2O emissions for systems in this region.

4. Conclusions

Application of fertilizer N improved seed, straw and chaff yield, and root mass of barley, wheat and canola grown in the second 4-yr rotation cycle of this study. No-till produced greater seed, straw and chaff yield of barley than CT, and straw retention increased seed, straw, chaff and root yield compared to straw removal for barley and wheat, and seed and straw yield for pea. The amount of N uptake and C removed in seed, straw, chaff and root was greater under NT than CT for barley, and also greater under S than NS for barley, pea and wheat in most cases. Nitrogen

fertilization increased N uptake and C removal in seed, straw, chaff and root for barley, wheat and canola. Soil moisture content in spring was higher under NT than CT and S than NS in the 0-15 cm depth, with the highest moisture content on NT + S in many cases. After eight crop seasons, tillage and straw management had no significant effect on total organic C (TOC) and N (TN) in the top 15 cm of soil, but light fraction organic matter (LFOM), C (LFC), and N (LFN) were generally greater with S than NS, and also greater or tended to be greater under NT than CT. There was no effect of tillage, straw and N fertilization on NH_4-N in soil, but S tended to have higher NO_3-N concentration in 0-15 cm soil than NS. The concentration of NO_3-N (though small) tended to increase with N rate in the 0-15, 15-30 and 30-60 cm soil layers. The S treatment had a lower proportion of wind-erodible dry aggregates (<0.83 mm diameter), greater proportion of larger (>38.0 mm) dry aggregates and a larger MWD of aggregates compared to NS treatment. There was no additional improvement in aggregation with the elimination of tillage. In fact, aggregation slightly decreased under NT compared to CT. These results indicate a reduced potential for soil erosion when crop residues are retained. The amount of N lost through N_2O-N emissions increased with N fertilization and was greater in CT than NT in some cases. The findings suggest that returning crop residue and no tillage would improve soil quality and productivity, and may also be better for the environment. Nitrogen fertilization, although improving crop production and some soil quality attributes, also increases the potential for NO_3-N leaching and N_2O-N emissions, especially when applied in excess of crop requirements for optimum yield.

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Table 1. The effect of tillage system, straw management and N rate on seed, straw, and chaff yield and root mass of barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Yield	Tillage[a]			Straw[b]			N Rate (kg N ha^{-1})				
(kg ha^{-1})	CT	NT	$LSD_{0.05}$	NS	S	$LSD_{0.05}$	0	40	80	120	$LSD_{0.05}$
Barley in 2002											
Seed	670	1014	104***	642	1042	104***	508	893	970	998	146***
Straw	1133	1394	144***	1039	1488	144***	700	1270	1440	1643	203***
Chaff	421	474	41*	423	472	41*	318	456	475	540	58***
Root	771	816	ns	754	834	66*	584	813	894	884	93***
Pea in 2003											
Seed	1992	1975	ns	1903	2065	94**	2007	1941	1929	2058	ns
Straw	1987	2046	ns	1889	2144	134***	1891	1885	2042	2247	190***
Chaff	739	713	ns	710	741	ns	659	715	711	817	102*
Root	480	480	ns	539	420	64***	457	448	480	535	ns
Wheat in 2004											
Seed	2896	2694	101***	2713	2877	101**	1942	2757	3214	3268	143***
Straw	5906	5776	ns	5659	6023	273*	4260	5757	6555	6790	386***
Chaff	1520	1517	ns	1462	1575	100*	1109	1495	1720	1751	141***
Root	1861	2117	180***	1906	2072	180*	1635	2190	2150	1980	255***
Canola in 2005											
Seed	2082	1909	90***	1967	2024	ns	925	1667	2566	2825	128***
Straw	4726	4504	214*	4611	4619	ns	2739	4566	5611	5544	303***
Chaff	613	618	ns	627	604	ns	427	623	703	708	90***
Root	1758	1736	ns	1762	1732	ns	1112	1671	1982	2223	180***

[a]CT and NT refer to conventional tillage and no-tillage, respectively.

[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.

*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 2. Effect of tillage x straw interaction on seed, straw, and chaff yield and root mass (averaged across four N rates) of barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Treatment		Yield (kg ha^{-1})			
Tillage[a]	Straw[b]	Seed	Straw	Chaff	Root
Barley in 2002					
CT	NS	562	965	407	793
	S	777	1300	435	750
NT	NS	723	1113	439	714
	S	1306	1675	508	918
	$LSD_{0.05}$	146***	ns	ns	93***
Wheat in 2004					
CT	NS	2745	5754	1483	1756
	S	3047	6057	1557	1966
NT	NS	2681	5563	1440	2056
	S	2708	5988	1594	2178
	$LSD_{0.05}$	143**	ns	ns	ns

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
, * and ns refer to significant treatment effects in ANOVA at $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 3. The effect of tillage system x N rate and straw management x N rate significant interactions on seed, straw and chaff yield, and root mass (0-15 cm) barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Parameter (kg ha^{-1})	Rate of N (kg N ha^{-1})								
	0	40	80	120	0	40	80	120	$LSD_{0.05}$
	CT[a]				NT[a]				
Barley seed yield in 2002	420	640	745	874	595	1146	1195	1122	207*
Wheat straw yield in 2004	4710	5931	6322	6660	3811	5583	6789	6920	546**
	NS[a]				S[a]				
Barley seed yield in 2002	418	691	714	747	597	1094	1226	1249	207*
Canola seed yield in 2005	883	1615	2662	2708	966	1720	2470	2941	180*
Canola straw yield in 2005	2629	4557	5907	5353	2849	4574	5315	5736	428*

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
•, *, ** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$ and not significant, respectively.

Table 4. The effect of tillage system, straw management and N rate on the amount of N uptake and C removal in seed, straw, chaff and root of barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

N uptake/ C removal (kg ha^{-1})	Tillage[a]			Straw[b]			N Rate (kg N ha^{-1})				
	CT	NT	$LSD_{0.05}$	NS	S	$LSD_{0.05}$	0	40	80	120	$LSD_{0.05}$
N uptake of barley in 2002											
Seed	16.9	24.2	2.64***	16.0	25.1	2.64***	11.6	20.0	24.4	26.2	3.74***
Straw	24.3	26.4	ns	22.0	28.7	2.93***	12.0	22.1	28.9	38.4	4.14***
Chaff	7.8	7.9	ns	7.8	7.9	ns	5.0	7.1	8.7	10.7	0.98***
Root	11.0	10.5	ns	10.5	11.0	ns	6.6	10.2	12.7	13.6	1.43***
C removal of barley in 2002											
Seed	293	442	45.2***	281	454	45.2***	222	387	424	437	63.9***
Straw	502	616	64.5**	463	655	64.5***	302	560	643	731	91.2***
Chaff	181	204	17.7*	182	203	17.7*	134	196	206	234	25.0***
Root	260	278	ns	252	286	21.5**	191	279	305	301	30.5***
N uptake of pea in 2003											
Seed	76.5	77.2	ns	73.2	80.6	3.80***	74.1	74.5	76.6	82.4	5.38*
Straw	22.1	23.5	ns	20.0	25.7	1.77***	20.2	20.8	23.7	26.6	2.50***
Chaff	14.2	14.1	ns	13.2	15.1	1.38**	12.8	13.3	14.1	16.3	1.96**
Root	8.7	8.6	ns	9.4	7.9	1.16*	8.3	7.9	8.6	9.6	ns
C removal of pea in 2003											
Seed	833	825	ns	796	863	39.4**	839	810	806	861	ns
Straw	797	823	ns	757	863	55.1***	767	761	819	893	77.9**
Chaff	308	298	ns	295	311	ns	277	300	297	339	42.1*
Root	175	175	ns	194	155	24.5**	165	163	178	193	ns
N uptake of wheat in 2004											
Seed	72.9	68.0	2.82**	67.9	73.1	2.82***	44.4	67.5	83.5	86.6	3.99***
Straw	53.7	54.3	ns	52.6	55.5	3.08*	31.8	46.7	63.1	74.5	4.35***
Chaff	22.2	21.9	ns	22.0	22.1	ns	14.1	19.4	26.6	28.2	2.62***
Root	13.2	15.0	1.91*	13.6	14.5	ns	9.2	13.7	16.6	16.9	2.69***
C removal of wheat in 2004											
Seed	1281	1192	44.2***	1201	1271	44.2**	857	1218	1423	1447	62.4***
Straw	2601	2543	ns	2493	2651	121.3*	1868	2544	2885	2991	171.6***
Chaff	682	676	ns	653	705	45.4*	494	666	769	786	64.2***
Root	555	626	64.4*	567	614	ns	476	601	671	615	91.1***
N uptake of canola in 2005											
Seed	71.7	64.6	4.79**	67.0	69.3	ns	25.6	48.2	86.3	112.5	6.78***
Straw	24.5	22.0	2.47*	22.6	23.9	ns	11.2	19.3	27.0	35.4	3.49***
Chaff	4.7	4.4	ns	4.4	4.7	ns	2.3	3.5	5.1	7.4	0.84***
Root	12.2	10.6	1.39*	11.8	11.0	ns	5.0	8.5	12.1	19.9	1.96***
C removal of canola in 2005											
Seed	1230	1128	52.6***	1167	1191	ns	554	999	1515	1649	74.4***
Straw	2128	2035	94.1*	2076	2087	ns	1251	2073	2509	2494	133.0***
Chaff	263	265	ns	270	258	ns	186	272	301	297	38.0***
Root	714	709	ns	711	712	ns	475	690	789	892	78.2***

[a]CT and NT refer to conventional tillage and no-tillage, respectively. [b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 5. Effect of tillage x straw interaction on N uptake and C removal in seed, straw, chaff or root (averaged across four N rates) of barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Parameter (kg ha^{-1})	CT[a]		NT[a]		
	NS[b]	S[b]	NS[b]	S[b]	$LSD_{0.05}$
Barley seed N uptake in 2002	14.1	19.7	17.8	30.6	3.7**
Barley root N uptake in 2002	11.4	10.6	9.6	11.4	1.4**
Barley seed C removed in 2002	245	340	316	568	64***
Barley root C removed in 2002	262	257	243	314	30***
Pea straw N uptake in 2003	20.4	23.9	19.6	27.5	2.5**
Wheat seed N uptake in 2004	68.1	77.7	67.6	68.4	4.0**
Wheat seed C removed in 2004	1218	1343	1184	1199	62**
Canola straw C removed in 2005	2082	2174	2071	2000	133*

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at P ≤0.10, P ≤0.01, P ≤0.001 and not significant, respectively.

Table 6. The effect of tillage system x N rate and straw management x N rate significant interactions on N uptake and C removal in seed, straw, chaff or root of barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Parameter (kg ha^{-1})	Rate of N (kg N ha^{-1})								
	0	40	80	120	0	40	80	120	$LSD_{0.05}$
	CT[a]				NT[a]				
Barley seed C removed in 2002	183	277	327	383	260	497	521	492	90*
Pea root N uptake in 2003	7.5	7.3	9.6	10.2	9.2	8.6	7.5	9.1	2.3*
Pea chaff C removed in 2003	307	303	275	347	246	296	319	330	60*
Wheat straw C removed in 2004	2069	2619	2781	2935	1666	2468	2989	3048	243**
	NS[b]				S[b]				
Barley seed N uptake in 2002	9.3	16.3	18.7	19.5	14.0	23.7	30.1	32.9	5.3*
Barley straw N uptake in 2002	11.2	19.4	25.2	32.2	12.8	24.9	32.5	44.6	5.9*
Barley root N uptake in 2002	7.2	10.9	11.5	12.5	6.0	9.5	13.8	14.7	2.0**
Barley seed C removed in 2002	182	301	312	328	261	474	536	547	90*
Barley chaff C removed in 2002	137	187	177	228	132	205	235	240	35*
Barley root C removed in 2002	202	276	268	264	180	282	342	338	43**
Pea seed N uptake in 2003	67.0	70.7	77.0	77.9	81.2	78.2	76.1	87.0	7.6*
Pea seed C removed in 2003	772	784	806	821	907	836	806	902	79*
Canola seed C removed in 2005	586	1039	1597	1699	522	960	1432	1598	105**
Canola straw C removed in 2005	1258	2120	2578	2557	1244	2024	2441	2432	188**

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
•, *, ** and ns refer to significant treatment effects in ANOVA at P ≤0.10, P ≤0.05, P ≤0.01 and not significant, respectively.

Table 7. The effect of tillage system, straw management and N rate on soil moisture in spring during the second 4-year crop rotation cycle (barley in 2002, pea in 2003, wheat in 2004 and canola in 2005) at Star City, Saskatchewan

Soil	Tillage[a]			Straw[b]			N Rate (kg N ha^{-1})		
depth (cm)	CT	NT	$LSD_{0.05}$	NS	S	$LSD_{0.05}$	0	120	$LSD_{0.05}$
Moisture content (%) 2002									
0-15	20.5	22.0	1.07**	20.3	22.2	1.07**	21.2	21.3	ns
15-30	16.5	18.4	1.90*	16.1	18.7	1.90**	17.8	17.1	ns
30-45	12.4	11.6	ns	11.2	12.9	1.70*	12.5	11.6	ns
45-60	9.1	9.1	ns	8.9	9.3	ns	8.7	9.4	ns
Moisture content (%) 2003									
0-15	21.2	22.3	ns	20.1	23.3	1.38***	21.3	22.2	ns
15-30	19.5	19.2	ns	18.8	19.9	1.04*	19.3	19.4	ns
30-45	14.9	13.2	1.68*	12.3	15.8	1.68***	13.7	14.4	ns
45-60	10.2	10.1	ns	9.2	11.2	1.61*	10.4	10.0	ns
Moisture content (%) 2004									
0-15	20.2	21.8	1.37*	20.0	22.0	1.37**	20.7	21.3	ns
15-30	17.5	17.6	ns	17.4	17.7	ns	17.3	17.8	ns
30-45	13.4	12.4	ns	12.4	13.4	ns	11.9	13.8	ns
45-60	10.2	11.1	ns	10.1	11.2	ns	10.4	10.9	ns
Moisture content (%) 2005									
0-15	22.0	22.0	ns	19.8	24.2	1.25***	21.3	22.7	1.25*
15-30	20.2	20.4	ns	19.8	20.7	0.75*	20.4	20.2	ns
30-45	18.9	18.9	ns	18.4	19.4	ns	18.4	19.4	ns
45-60	14.5	13.8	ns	13.5	14.8	ns	14.5	13.8	ns

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, *, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 8. Effect of tillage x straw interaction on soil moisture (averaged across four N rates) for barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Soil moisture (%)	CT[a]		NT[a]		$LSD_{0.05}$
	NS[b]	S[b]	NS[b]	S[b]	
45-60 cm in 2002	9.6	8.7	8.1	10.0	1.6*
30-45 cm in 2003	14.0	15.8	10.6	15.9	2.4*
0-15 cm in 2004	19.7	207	20.2	23.4	1.9*
45-60 cm in 2004	10.5	9.9	9.7	12.5	2.5*
45-60 cm in 2005	13.0	16.0	14.0	13.7	2.8*

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 9. The effect of tillage system x N rate and straw management x N rate significant interactions on soil moisture for barley in 2002, pea in 2003, wheat in 2004 and canola in 2005 at Star City, Saskatchewan

Soil moisture (%)	Rate of N (kg N ha^{-1})				$LSD_{0.05}$
	0	120	0	120	
	CT[a]		NT[a]		
15-30 cm in 2002	17.6	15.3	18.0	18.8	1.5*
30-45 cm in 2002	13.7	11.2	11.4	11.9	2.4*
45-60 cm in 2002	9.4	8.8	8.1	10.0	1.6*
	NS[b]		S[b]		
0-15 cm in 2005	19.6	20.1	23.0	25.4	1.8*

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
•, *, ** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$ and not significant, respectively.

Table 10. The effect of tillage system, straw management and N rate on the mass of total organic C (TOC) and N (TN), and light fraction organic matter (LFOM), C (LFOC) and N (LFN) in autumn 2005 after the second 4-year crop rotation cycle at Star City, Saskatchewan

Soil	Tillage[a]			Straw[b]			N Rate (kg N ha^{-1})		
depth (cm)	CT	NT	$LSD_{0.05}$	NS	S	$LSD_{0.05}$	0	80	$LSD_{0.05}$
Mass of TOC (Mg C ha^{-1})									
0-5	23.46	23.51	ns	23.72	23.52	ns	23.35	23.62	ns
5-10	25.22	24.27	ns	25.57	23.91	ns	25.21	24.27	ns
10-15	13.19	13.92	ns	13.68	13.43	ns	13.86	13.26	ns
0-15	61.87	61.70	ns	62.98	60.59	ns	62.42	61.15	ns
Mass of TN (Mg N ha^{-1})									
0-5	1.88	1.94	ns	1.94	1.89	ns	1.88	1.95	ns
5-10	2.12	2.05	ns	2.15	2.02	ns	2.13	2.03	ns
10-15	1.20	1.32	ns	1.28	1.24	ns	1.29	1.23	ns
0-15	5.21	5.32	ns	5.38	5.14	ns	5.32	5.21	ns
Mass of LFOM (Mg LFOM ha^{-1})									
0-5	14.80	16.49	ns	13.29	18.00	2.39***	13.86	17.42	2.39**
5-10	9.43	9.84	ns	10.24	9.02	ns	8.90	10.37	ns
10-15	4.08	4.55	ns	4.35	4.28	ns	3.93	4.70	ns
0-15	28.29	30.86	ns	27.87	31.29	3.76*	26.68	32.48	3.76**
Mass of LFOC (Mg C ha^{-1})									
0-5	3.126	3.673	0.476*	2.644	4.155	0.476***	2.964	3.835	0.476**
5-10	1.789	1.802	ns	1.920	1.671	0.222*	1.641	1.950	0.222**
10-15	0.802	0.794	ns	0.789	0.807	ns	0.698	0.898	ns
0-15	5.706	6.269	0.689*	5.350	6.625	0.689***	5.300	6.675	0.689***
Mass of LFN (Mg N ha^{-1})									
0-5	0.185	0.217	0.025*	0.169	0.233	0.025***	0.174	0.228	0.025***
5-10	0.106	0.107	ns	0.113	0.100	0.014*	0.097	0.116	0.014**
10-15	0.038	0.039	ns	0.039	0.038	ns	0.034	0.043	ns
0-15	0.312	0.356	0.040*	0.319	0.350	0.040*	0.288	0.381	0.040***

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, *, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

Table 11. The effect of tillage system, straw management and N rate on the NO_3-N and NH_4-N concentrations in the soil in autumn 2005 after the second 4-year crop rotation cycle at Star City, Saskatchewan

Soil depth (cm)	Tillage[a]			Straw[b]			N Rate (kg N ha^{-1})				
	CT	NT	$LSD_{0.05}$	NS	S	$LSD_{0.05}$	0	40	80	120	$LSD_{0.05}$
Concentration of NO_3-N (mg N kg^{-1})											
0-15	4.79	4.57	ns	4.17	5.20	0.58***	3.32	3.79	4.74	6.90	0.82***
15-30	1.33	1.26	ns	1.24	1.35	ns	1.12	0.99	1.28	1.79	0.24***
30-60	1.33	1.28	ns	1.26	1.35	ns	1.13	1.02	1.17	1.89	0.28***
Concentration of NH_4-N (mg N kg^{-1})											
0-15	5.47	5.74	ns	5.55	5.66	ns	5.47	5.27	5.91	5.77	ns
15-30	5.67	5.80	ns	5.52	5.96	0.42*	5.52	5.70	6.14	5.58	ns
30-60	5.01	5.01	ns	4.58	5.44	0.51**	4.83	5.36	5.06	4.80	ns

[a]CT and NT refer to conventional tillage and no-tillage, respectively. [b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at P ≤0.05, P ≤0.01, P ≤0.001 and not significant, respectively.

Table 12. The effect of tillage system, straw management and tillage system x straw management on dry soil aggregate distribution percentage for each size and mean weight diameter (MWD) in autumn 2005 at Star City Saskatchewan

Treatments				Percentage for each soil aggregate size (mm)						
Tillage[a]	Straw[b]	N Rate kg N ha^{-1}	MWD (mm)	< 0.42	0.42 to 0.83	0.83 to 2.0	2.0 to 6.4	6.4 to 12.7	12.7 to 38.0	> 38.0
						Tillage x straw interaction				
CT	NS		19.74	11.07	5.98	3.47	14.61	10.96	38.64	15.26
	S		23.95	6.66	4.69	3.14	13.76	9.93	38.14	23.68
NT	NS		16.88	13.26	7.63	4.48	15.56	10.84	38.21	10.02
	S		21.71	7.73	5.60	3.78	14.67	10.18	39.25	18.80
	$LSD_{0.05}$		ns	ns	0.65*	ns	ns	ns	ns	ns
						Tillage system				
CT mean			21.84	8.87	5.34	3.31	14.18	10.44	38.39	19.47
NT mean			19.29	10.50	6.62	4.13	15.11	10.51	38.73	14.41
$LSD_{0.05}$			1.34***	0.92***	0.46***	0.26***	0.79*	ns	ns	2.91**
						Straw management				
	NS mean		18.31	12.17	6.81	3.98	15.08	10.90	38.42	12.64
	S mean		22.82	7.20	5.14	3.46	14.21	10.05	38.70	21.24
	$LSD_{0.05}$		1.34***	0.92***	0.46***	0.26***	0.79*	0.53**	ns	2.91***
						N Rate				
		0	19.11	11.89	6.56	3.84	14.74	10.66	37.79	14.54
		40	20.43	9.73	6.03	3.76	14.65	10.34	38.99	16.50
		80	20.94	9.07	5.81	3.65	14.47	10.42	38.24	17.34
		120	21.78	8.04	5.51	3.62	14.75	10.48	38.23	19.38
		$LSD_{0.05}$	1.90*	1.30***	0.65*	ns	ns	ns	ns	ns

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at P ≤0.05, P ≤0.01, P ≤0.001 and not significant, respectively.

Table 13. Estimated cumulative N_2O-N emissions for various tillage system, straw management and N rate treatments in 2002, 2003, 2004 and 2005 at Star City, Saskatchewan

Treatments			N_2O-N loss (g N ha^{-1})			
Tillage[a]	Straw[b]	N rate (kg ha^{-1})	2002	2003	2004	2005
Tillage x straw x N interaction						
CT	NS	0	30	100	80	520
		120	240	120	1170	820
	S	0	40	100	70	470
		120	280	140	1300	830
NT	NS	0	20	80	100	320
		120	200	140	800	1020
	S	0	40	90	160	290
		120	230	150	670	1130
$LSD_{0.05}$			ns	ns	ns	ns
Tillage system						
CT			150	120	660	660
NT			120	120	430	690
$LSD_{0.05}$			ns	ns	202*	ns
Straw management						
	NS		120	110	540	670
	S		150	120	550	680
	$LSD_{0.05}$		ns	ns	ns	ns
N rate						
		0	30	90	100	400
		120	240	140	990	950
		$LSD_{0.05}$	59***	35***	202***	302***
Tillage x straw interaction						
CT	NS		140	110	630	670
	S		160	120	690	650
NT	NS		110	110	450	670
	S		140	120	420	710
	$LSD_{0.05}$		ns	ns	ns	ns
Tillage x N interaction						
CT		0	30	100	80	490
		120	260	130	1240	820
NT		0	30	80	130	300
		120	210	150	740	1070
		$LSD_{0.05}$	ns	ns	405**	ns
Straw x N interaction						
NS		0	30	90	90	420
		120	220	140	990	920
S		0	40	90	120	380
		120	250	150	990	980
		$LSD_{0.05}$	ns	ns	ns	ns

[a]CT and NT refer to conventional tillage and no-tillage, respectively.
[b]NS and S refer to no straw (straw removed) and straw (straw retained), respectively.
*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.